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博士論文要旨

Intersegmental Dynamics and Optimality in Rapid Aiming Movements

Masashi Yoshida　　Supervisor : Shuji Suzuki

The control of limb movements is essential for everyday life. Day and night, humans are required to reach for a target in space, to pick up an object, and to make other wide varieties of goal-directed movements. Many of those movements are performed so effortlessly; yet are necessary to compromise with an inherent nature of human motor behavior, *a speed-accuracy trade-off.*

A great deal of research over the past century has clearly demonstrated that movements toward a target consist of two components, an *initial impulse (or primary submovement)* followed by *current control* (or *corrective submovement*) (e.g., Meyer et al., 1988; Woodworth, 1899). In essence, visual feedback reduces spatial errors to a greater extent. Temporal constraints of the movements, however, restrict time to process visual feedback (e.g., Keele & Posner, 1968), and thus the accuracy advantage by vision gradually decreases as a function of the movement speed. Meanwhile, the magnitude of the initial impulse has a lawful relation to the dispersion of the primary submovement endpoints that defines the extent to which feedback-based corrective processes must operate (e.g., Schmidt et al., 1979).

Recently, much attention has been paid to optimal control strategies in rapid aiming movements (e.g., Khan & Franks, 2000). Typically, a performer with vision tends to increase the velocity of the primary submovement to bring the limb to the vicinity of the target quickly. This strategy allows the performer more time available for visual feedback utilization in the corrective submovements. By contrast, a performer without vision produces a slower but less variable primary submovement to abandon visually-guided error corrections.

Despite a considerable amount of research, only limited attempts have been made to quantify the mechanical causes of rapid aiming movements. Limbs are systems of linked bodies, and thus the motion of a particular segment affects other segments in a kinetic chain, even if a given segment is not exposed to active muscle forces. Studies merely manipulating kinematic parameters, however, cannot account for these motion-dependent effects.

A method of the intersegmental dynamics is, by contrast, useful to estimate the active and passive contributions to the movement trajectories (e.g., Schneider et al., 1989). With this method, net joint moment (NJM) can be partitioned into its three moment components. The three moment components were: (1) generalized-muscle moment (GMM) - moment arising from active muscle forces and other soft tissue forces crossing the joint; (2) motion-dependent moment (MDM) - moment arising from passive-interactive forces by dynamic interactions between segments; and (3) gravity-dependent moment (GDM) - moment arising from gravitational forces.

In the context, this study dealt with the intersegmental dynamics of rapid aiming movements to provide further evidence on how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy. Of particular interest was how humans adapted their control strategies in ensuring optimal performance.

Experiment 1: Inherent Errors

In Experiment 1, spatial accuracy of rapid aiming movements was examined by differentiating limb dynamics while keeping limb kinematics constant. Five male participants performed an 80-cm hand-held stylus movement to a target as accurately as possible with three temporal constraints: 300, 400, and 500 ms (Fig. 1). The movements were performed while lying face either left or

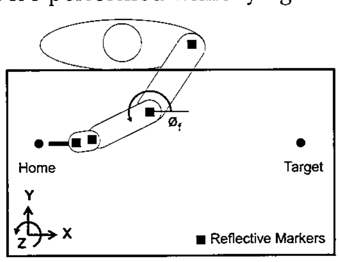

Fig. 1 .An overhead view of the experimental setup

right on a flat bench; thus either (a) downward movements with gravity (DM) or (b) upward movements against gravity (UM) in the vertical plane.

An analysis of the intersegmental dynamics revealed that an 80-cm hand-held stylus movement with gravity (i.e., DM) or against gravity (i.e., UM) yielded nearly identical limb kinematics (i.e., angular displacement, velocity, and acceleration), but completely different limb dynamics. In DM, gravity (i.e., GDM) acted as a limb extensor, and therefore assisted in accelerating yet resisted in decelerating the limb to a target. In UM, on the other hand, gravity acted as a limb flexor, and therefore resisted in accelerating yet assisted in decelerating the limb to a target. As a consequence, UM required greater active muscle forces (i.e., GMM) in the acceleration phase than DM.

Consistent with a number of previous findings, spatial errors increased with temporal constraints of the movements (or the average velocity of the movements), indicating speed-accuracy trade-offs. More importantly, UM resulted in larger spatial errors in comparison to DM. Because of no significant differences in movement time or nearly identical limb kinematics between test conditions, the larger spatial errors by UM was attributable to an increase in the level of active muscle force output.

Experiment 2: Control Strategies

The purpose of Experiment 2 was to examine the effects of practice and vision on the intersegmental dynamics of rapid aiming movements. Twenty participants (6 females and 14 males) performed a 90-cm movement to a target for 560 trials as quickly and accurately as possible in the horizontal plane. They were randomly assigned into either a full-vision (FV) group or a no-vision (NV) group, practicing the task with or without vision, respectively, throughout each trial. Vision was modified with a pair of occlusion goggles, in which the lenses on these goggles were either transparent allowing vision or translucent occluding vision without affecting the quantity of light reaching the eyes.

With practice, participants improved their performance by minimizing movement time without sacrificing spatial errors. Vision yet ensured more accurate performance throughout practice. In addition, they exploited the passive-interactive properties of the moving system (i.e., MDM), together with the mechanical properties of the muscle (i.e., GMM), to properly accelerate the limb to a target (i.e., NJM). Essentially, all moment components increased in magnitude with practice.

However, the aspects of the intersegmental dynamics were quite distinctive between vision conditions. Specifically, comparing to the other vision group, the FV group produced greater average GMM in the acceleration phase; whereas, the NV group produced greater average GMM in the deceleration phase.

Experiment 3: Instant Adaptation

As a subsequent experiment, Experiment 3 examined the effect of withdrawing vision on the intersegmental dynamics of rapid aiming movements. Following Experiment 2, both the FV and NV participants completed a transfer test under the NV condition.

The withdrawal of vision later in practice from the FV group caused an increase in spatial errors; furthermore a decrease in the magnitudes of moments, indicating a specificity of practice effect (e.g., Proteau et al., 1987). This specificity of practice effect on the intersegmental dynamics clearly indicated that the FV participants did not accelerate their movements the same as when vision was available during practice.

General Discussion

The results clearly demonstrate that errors are inherent in the primary submovements that increase as a function of the level of active muscle force output, causing speed-accuracy trade-offs. To ensure optimal performance, however, different control strategies are possible depending on the abilities to use on-line visual feedback. More importantly, humans can instantly adapt their control strategies to avoid a deteriorating loss in performance. Such instant adaptation of control strategies is interpreted as the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing.

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